Visual Abstract

Experimental and computational study on dynamic analysis of cracked simply supported structures under moving mass

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ABSTRACT. In this study, the influences of crack parameters like crack location from the left end, crack height, number of cracks and the magnitude of mass and the velocity of the transit load on the vertical displacements of the cracked simply supported beams subjected to transit mass are investigated. The transverse open cracks with numerous damage scenerios are considered for the mathematical modelling of the system. The governing equations of motion for the system have been obtained and the equations have been solved by the help of Duhamel integral technique. The theoretical formulation has been exemplified with numerical studies. By utilizing ANSYS Workbench 2020, transient structural analysis has been carried out. The mode shapes and the frequency ratios of damaged simply supported beam have also been determined. To validate the numerical and FEM models, the experiments with damaged beams have been carried out in the laboratory. It has been proven that the results of the theoretical and FEM models are well convergent with the experimental data. The results gathered from the numerical analysis, FEA as well as experimental study have been presented with comparative graphs and tables. The outcomes of the examinations have been interpreted in the conclusions part. It has been observed that subject parameters are of considerable significance on the time dependent response of the cracked beams.

KEYWORDS. Damaged simply supported beam; Moving load; FEA; Experimental study; Duhamel integral.

OPEN ACCESS

Citation: Bulut, C. O., Jena, S. P., Kurt, S., Experimental and computational study on dynamic analysis of cracked simply supported structures under moving mass, Frattura ed Integrità Strutturale, 60 (2022) 114-133.

Received: 17.11.2021
Accepted: 13.01.2022
Online first: 27.01.2022
Published: 01.04.2022

INTRODUCTION

The beam like structures subjected to transit mass have been the conventional subject of interest for many scientists. Aerospace and defense industries, cranes, bridges, railways engineering etc. are the areas in which the engineering structures can be seen. The main purpose of the investigation of the problems of the moving mass is to understand the behaviour of the structures and develop the design accordingly. Another advantage of these investigations is the early detection of any kind of deterioration. Once the behaviour of the structure is known in advance, some precautions can be taken before any damage occurs either in desing phase or during the operation. Many researchers and scientists studied on these problem for the past decades and contibuted a lot progressively.

Sekhar [1] worked on damage detecting techniques that helped understand the beaviour of the structure. Ouyang [2] has developed a tutorial in order to demonstrate the transit mass problems with various examples. Reis and Pala [3], introduced the significance of the influences of the acceleration of centrifugal and Coriolis's on the vibrations of damaged cantilever structure. Reis and Pala [4] applied the similar formulation for a single cracked beam using Duhamel integral technique. Perturbation methods were employed in the article of Bulut and Kelesoglu [5] to inspect the time dependent characteristics of a structure under a moving load. Bilello and Bergman [6] concluded their analytical study with experimantal verifications. Ariaei et al. [7] applied finite element technique for the analysis of structures that contain different type of cracks under moving mass load. From the work by Jena et al. [8], it is understood that different crack types can affect the vibration characteristics of damaged beams, especially, the influence of the inclination angle of the crack was proposed as a novelty. Work by Jena and Parhi [9] includes numerical, FEA and experimental analysis of the cracked structures under moving mass through a comparative attitude. They investigated the effects of different types of cracks. Lin and Chang [10] created a new methodology to analyze the dynamics of a damaged cantilever structure subjected to transit load. The article of Fu [11] emphasizes the existence of the cracks on the vibrations of a bridge like structure. NT Khiem and PT Hang [12], studied on dynamic analysis of the damaged structure along with the damage detection using the sensors. Ozturk et al. [13] investigated damaged fixed-fixed stucture on an elastic foundation subjected to a concentrated moving mass by embodying the Newmark integration method. Attar et al. [14] explored the influences of some parameters on the vibration response of damaged Timoshenko beam with an elastic support. Aied and Gonzalez [15] investigated the vibration characteristics of a simply supported viscoelastic beam under the transit mass by defining a dynamic modulus pertaining to the rate of strain. Demirtas and Ozturk [16] extracted the mode shapes of multi-storey frames subjected to train loads and the results are illustrated with various graphs. Tan et al. [17] analyzed the behavior of damaged Timoshenko beams and the transit load has been modelled as a system of a spring and a mass. Hosseini et al. [18] observed the forced vibrations of carbon nanotubes subjected to moving mass. They utilized different models like Bishop and Rayleigh. Omolofe et al. [19] explored the influences of braking, acceleration, and constant velocity on the vibrations of prestresed structure under transit mass. Zhou and Liu [20] explained in their work the effects of and the impact factor and the propogation of crack on the vibrations of a damaged concrete structure subjected to a transit vehicle.

Green function is one of the common methods used for determining the vibration behavior of damaged structures. This method has been utilized in some latest works. Ghannadiasl and Ajirlou [21] investigated the dynamics of damped structure under a transit mass using Green function method. In another paper of Ghannadiasl and Ajirlou [22] the solution has been given analitically with the help of dynamic Green function. The response of damaged structure under concentrated mass has been obtained and the numerical results have been validated with experimental tests. Pala et al. [23] investigated vibration of a damaged Timoshenko beam with different end states considering the effect of the damping. The frequencies of cracked structures have been calculated as per damage severity and position. Bulut et al. [24] investigated the influences of crack properties on the dynamic deflection of damaged cantilever beams. They performed finite elements analyis along with a numerical study with numerous exemplifications of various damage configurations. It has been observed that the numerical results are really close to FEA results with little deviations. Seguini et al. [25] investigated the effects of crack depth on the dynamic behaviour of steel beam using experimental and artificial neural methods.

From the literature review, it has been understood that a comprehensive study regarding the response of damaged simply supported beams with numerical, FEM analysis along with experimental validations in a comparative way is lacking. It is aimed to fill this gap in the literature with this paper. The performances of Numerical, FEA along with Experimental works are very scanty in the litarature. As the previous works are concerned the formulation of the FEA along with experimental procedures are quiet good. Again, the developement of the experimental set up is quiet noble one with the

use of PLC controller. The errors(Results and Discussion section) which are obtained from this study are quiet less as comparison to the others works like Jena et al.[8,9].
The main points of this paper are as following: The effects of amount of cracks, crack depth and crack position on the dynamics of cracked beams have been scrutinized.The impact of velocity and mass of moving load have been explored. Transient analysis has been performed in ANSYS to extract the response of damaged structures carrying transit load. Laboratory tests have been conducted to verify the validity of the theoretical and FEM models. The deviations of numerical and FEA results from the experimental results have been calculated.

THE MATHEMATİCAL MODEL AND THE PROBLEM FORMULATION

In this article, damaged simply supported beams with two and three cracks under the influence of a transit mass have been investigated. The equations of motion have been extracted as per the double damaged beam and then adjusted for three cracked simply supported beam. In Fig. 1, double cracked simply supported beam- transit mass structure is illustrated. The governing equation of motion can be obtained per Fryba [26] and Michaltsos and Kounadis [27] as:

$$EI\, y'''' + m\,\ddot{y} = \left[Mg - M\left(\ddot{y} + v^2 y'' + 2v\,\dot{y}' \right) \right] \delta(x - vt) \tag{1}$$

In Eqn. 1 , EI is the beam rigidity, y is the displacement of the beam in vertical direction, m is the beam mass divided by beam length, M is the transit load, v is the speed of the moving load, δ is Dirac delta function. $\ddot{y}$, $v^2 y''$ and $2v\dot{y}'$ stand for the vertical, centrifugal and Coriolis's accelerations respectively. In this formulation, '' ' shows the derivation with respect to x while '.' stands for the derivation with respect to time t. Here 'g' is the acceleration due to gravity.

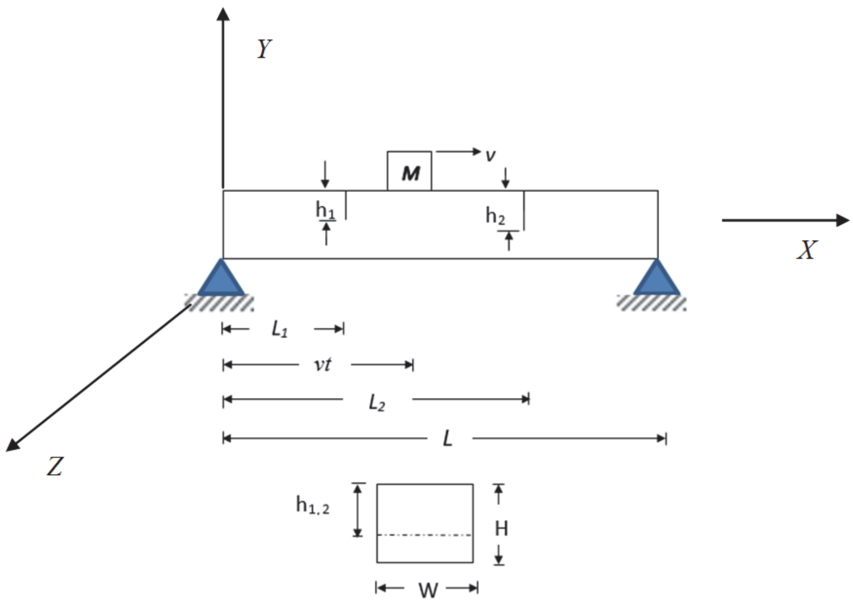

Figure 1: Model for damaged simply supported beam with two cracks - transit load

The general solution of the equation can be written with the expansion of series as follows:

$$y(x,t) = \sum_{i=1}^{i} S_i(x) N_i(t) \tag{2}$$

$S_i(\mathrm{x})$ is obtained as follows where

$$S_i^4(x) - \lambda_i^4 S_i(x) = 0$$

$$\lambda_i^4(x) = \frac{m\,\omega_i^2}{EI} \tag{3}$$

Here,
ω_i : natural frequency of the damaged beam
$S_i(\mathrm{x})$: Eigen functions
$N_i(t)$: Generalized coordinates
Due to the presence of the transverse and open cracks in the structure, the beam modelling has been done as three subparts for two cracks and four beam segments for three cracks.
For a simply supported beam with two cracks, the solution for Eqn. (3) can be written as below:
For the first beam subdivision ($0 \le vt \le L_1$)

$$S_{i1}(vt) = A_{i1}\sin(\lambda_i vt) + B_{i1}\cos(\lambda_i vt) + C_{i1}\sin h(\lambda_i vt) + D_{i1}\cosh(\lambda_i vt) \tag{4.1}$$

For the second beam subpart ($L_1 \le vt \le L_2$)

$$S_{i2}(vt) = A_{i2}\sin(\lambda_i vt) + B_{i2}\cos(\lambda_i vt) + C_{i2}\sin h(\lambda_i vt) + D_{i2}\cosh(\lambda_i vt) \tag{4.2}$$

For the third beam part ($L_2 \le vt \le L$)

$$S_{i3}(vt) = A_{i3}\sin(\lambda_i vt) + B_{i3}\cos(\lambda_i vt) + C_{i3}\sin h(\lambda_i vt) + D_{i3}\cosh(\lambda_i vt) \tag{4.3}$$

While the simple support prevents the deflection, it allows to rotate where it is located. The end conditions of the proposed simply supported beam is explained as follows. One end condition is geometric and the other one is dynamic. At $x=0$, $y(0,t)=0$ and $y''(0,t)=0$. At $x=L$, $y(L,t)=0$ and $y''(L,t)=0$.
Applying the end states, $A_i, B_i, C_i D_i$ constants can be determined as explained by Thomson [28]. In this investigation, crack model in Dash's work [29] has been considered. He explained the cracks analytically in detail in his model.
Eqn. (2) has been put into Eqn. (1) and then multipled by $S_j(\mathrm{x})$. After that the equation is integrated over the length of beam. Referring to Reis and Pala[4], The features of orthogonality and the Dirac delta function are taken into consideration, embodying some arrangements, the equation can be given as stated in Eqn. (5) and Eqn.

$$\begin{aligned}
&\sum_{i=1}^{i}\left(\ddot{N}_i + \omega_i^2 N_i\right)\int_0^L S_i(x)S_j(x)\,dx = \frac{Mg}{m}\int_0^L S_j(x)\,\delta(x-vt)\,dx \\
&-\frac{M}{m}\left[\sum_{j=1}^{i}\ddot{N}_j\int_0^L S_i(x)S_j(x)\,\delta(x-vt)\,dx\right] \\
&-\frac{M}{m}\left[\sum_{j=1}^{i}v^2 N_j\int_0^L S_i''(\mathrm{x})S_j(x)\,\delta(x-vt)\,dx\right] \\
&-\frac{M}{m}\left[\sum_{j=1}^{i}2v\,\dot{N}_j\int_0^L S_i'(\mathrm{x})S_j(\mathrm{x})\;\delta(x-vt)\,dx\right]
\end{aligned} \tag{5}$$

$$\ddot{N}_i+\omega_i^2 N_i=\frac{M}{m}S_i(vt)\left(g-\left[\sum_{j=1}^{i}\ddot{N}_j S_j(vt)\right]-\left[v^2\left[\sum_{j=1}^{i}N_j S_j''(vt)\right]\right]-\left[2v\sum_{j=1}^{i}\dot{N}_j S_j'(vt)\right]\right) \tag{6}$$

Due to the orthogonality of the eigenfunctions, we can write below equation:

$$\int_0^L S_i^2\,dx=\int_0^L S_j^2\,dx=\int_0^{L_1} S_{i1}^2\,dx+\int_{L_1}^{L_2} S_{i2}^2\,dx+\int_{L_2}^{L} S_{i3}^2\,dx \tag{7}$$

The equation (6) can be resolved utlizing the method proposed by Picard. In this method, basically an iteration is done by accepting the first one on the right side of the equation and neglecting the others. As per Lal M, Moffatt D [30], Michaltsos and Kounadis [27], Collins [31] , recalling the Picard's method the following expresions are obtained;
For

$$0\le t\le\frac{L_1}{v}$$

$$\ddot{N}_i+\omega_i^2 N_i=\frac{Mg}{m}S_{i1}(vt) \tag{8.1}$$

For

$$\frac{L_1}{v}\le t\le\frac{L_2}{v}$$

$$\ddot{N}_i+\omega_i^2 N_i=\frac{Mg}{m}S_{i2}(vt) \tag{8.2}$$

For

$$\frac{L_2}{v}\le t\le\frac{L}{v}$$

$$\ddot{N}_i+\omega_i^2 N_i=\frac{Mg}{m}S_{i3}(vt) \tag{8.3}$$

The solution of the Eqn. (6) can be given as follows for the homogeneous part:

For

$$t\le\frac{L_1}{v}$$

$$N_{i1})_h=\theta_1\sin[\omega_i t]+\theta_2\cos[\omega_i t] \tag{9}$$

The particular solution of Eqn. (6) can be given as follows if $\Omega_i=\lambda_i v$

$$(N_{i1})_p=A_{i1}^*\sin(\Omega_i t)+B_{i1}^*\cos(\Omega_i t)+C_{i1}^*\sinh(\Omega_i t)+D_{i1}^*\cosh(\Omega_i t) \tag{10}$$

Once the values from the Eqn. (10) are applied into Eqn. (8), Eqn. (11) is obtained

$$A_{i1}^{*} = \frac{Mg\,A_{i1}}{m\left(\omega_i^2 - \Omega_i^{\,2}\right)}, B_{i1}^{*} = \frac{Mg\,B_{i1}}{m\left(\omega_i^2 - \Omega_i^{\,2}\right)}, C_{i1}^{*} = \frac{Mg\,C_{i1}}{m\left(\omega_i^2 + \Omega_i^{\,2}\right)},\ D_{i1}^{*} = \frac{Mg\,D_{i1}}{m\left(\omega_i^2 + \Omega_i^{\,2}\right)} \tag{11}$$

The sum of both solution expresses the general solution of Eqn. (6) for $\frac{L_1}{V}$. It can be provided as:

$$N_i\left(t\right) = (N_{i1})_h + (N_{i1})_p = \theta_1 \sin\left[\omega_i t\right] + \theta_2 \cos\left[\omega_i t\right] + (N_{i1})_p \tag{12}$$

To be able to calculate θ_1 and θ_2, initial states ($N_{i1}\left(0\right) = \dot{N}_{i1}\left(0\right) = 0$) are used, and constant terms are calculated as

$$\theta_1 = \frac{\left[A_{i1}^{*} + C_{i1}^{*}\right]\Omega_i}{\omega_i}, \theta_2 = -\left(B_{i1}^{*} + D_{i1}^{*}\right) \tag{13}$$

Since $\theta_1, \theta_2, A_{i1}^{*}, B_{i1}^{*}, C_{i1}^{*}, D_{i1}^{*}$ have been found, Eqn. (12) can be stated as

$$N_{i1}\left(t\right) = N_{j1}\left(t\right) == \theta_1 \sin[\omega_i t] + \theta_2 \cos\left[\omega_i t\right] + A_{i1}^{*} \sin[\Omega_i t\,] + B_{i1}^{*} \cos\left[\Omega_i t\right] + C_{i1}^{*} \sinh[\Omega_i t] + D_{i1}^{*} \cosh[\Omega_i t\,] \tag{14}$$

Using Eqn. (14), $N_i, \dot{N}_i$ and $\ddot{N}_i$ can be found.

Once $N_i\left(t\right)$ in Eqn. (14) is applied into Eqn. (6) for beam subpart $t \le \frac{L_1}{V}$ of Eqn. (8), we get R_{i1}

$$\ddot{N}_i + \omega_i^2 N_i = \frac{2M}{mL} S_i\left(vt\right)\left(g - \left[\sum_{j=1}^{i} \ddot{N}_{j1} S_{j1}\left(vt\right)\right] - \left[v^2\left[\sum_{j=1}^{i} N_{j1} S''_{j1}\left(vt\right)\right]\right] - \left[2v \sum_{j=1}^{i} \dot{N}_{j1} S_{j1}'\left(vt\right)\right]\right) = R_{i1} \tag{15}$$

Eqn. (14) is inserted into the right side of Eqn. (15), Eqn. (16) is found for $t \le \frac{L_1}{V}$,

$$\ddot{N}_i + \omega_i^2 N_i = R_{i1} \tag{16}$$

Eqn. (16) can be defined by taking the initial conditions into consideration as follows

For the first beam segment, $t \le \frac{L_1}{v}$

$$N_i\left(t\right) = \frac{1}{\omega_i} \int_0^{\frac{L_1}{v}} R_{i1}\left(\tau\right) \sin\left[\omega_i\left(t - \tau\right)\right] d\tau \tag{17}$$

For the second and third beam segments, the same is embodied and Eqn. (18) and Eqn. (19) are determined as follows. It should be noted that initial conditons are not zero now.

For the second beam part, $\frac{L_1}{v} \le t \le \frac{L_2}{v}$

$$N_i\left(t\right) = \frac{1}{\omega_i} \int_0^{\frac{L_1}{v}} R_{i1}\left(\tau\right) \sin[\omega_i\left(t - \tau\right)] d\tau + \frac{1}{\omega_i} \int_{\frac{L_1}{v}}^{\frac{L_2}{v}} R_{i2}\left(\tau\right) \sin\left[\omega_i\left(t - \tau\right)\right] d\tau \tag{18}$$

For the third beam part, $\frac{L_2}{v} \le t \le \frac{L}{v}$

$$N_i(t)=\frac{1}{\omega_i}\int_0^{\frac{L_1}{v}}\mathrm{R}_{i1}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\frac{1}{\omega_i}\int_{\frac{L_1}{v}}^{\frac{L_2}{v}}\mathrm{R}_{i2}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\frac{1}{\omega_i}\int_{\frac{L_2}{v}}^{\frac{L}{v}}\mathrm{R}_{i3}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau \qquad (19)$$

The formulation can be written according to the desired number of cracks in the structure similarly. In this study, triple cracked beam has been analyzed and $\mathrm{N_i}(t)$ has been determined accordingly.

After some simplifications, the following formulation is obtained.

For the first beam segment, $t\leq\frac{L_1}{v}$

$$N_i(t)=\frac{1}{\omega_i}\int_0^{\frac{L_1}{v}}\mathrm{R}_{i1}(\tau)\sin[\omega_i(t-\tau)]d\tau \qquad (20)$$

For the second beam segment, $\frac{L_1}{v}\leq t\leq\frac{L_2}{v}$

$$N_i(t)=\frac{1}{\omega_i}\int_0^{\frac{L_1}{v}}\mathrm{R}_{i1}(\tau)\sin[\omega_i(t-\tau)]d\tau+\frac{1}{\omega_i}\int_{\frac{L_1}{v}}^{\frac{L_2}{v}}\mathrm{R}_{i2}(\tau)\sin[\omega_i(t-\tau)]d\tau \qquad (21)$$

For the third beam segment, $\frac{L_2}{v}\leq t\leq\frac{L_3}{v}$

$$N_i(t)=\frac{1}{\omega_i}\int_0^{\frac{L_1}{v}}\mathrm{R}_{i1}(\tau)\sin[\omega_i(t-\tau)]d\tau+\frac{1}{\omega_i}\int_{\frac{L_1}{v}}^{\frac{L_2}{v}}\mathrm{R}_{i2}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\frac{1}{\omega_i}\int_{\frac{L_2}{v}}^{\frac{L_3}{v}}\mathrm{R}_{i3}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau \qquad (22)$$

For the fourth beam segment, $\frac{L_3}{v}\leq t\leq\frac{L}{v}$

$$\begin{aligned}N_i(t)=&\frac{1}{\omega_i}\int_0^{\frac{L_1}{v}}\mathrm{R}_{i1}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\frac{1}{\omega_i}\int_{\frac{L_1}{v}}^{\frac{L_2}{v}}\mathrm{R}_{i2}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\\&+\frac{1}{\omega_i}\int_{\frac{L_2}{v}}^{\frac{L_3}{v}}\mathrm{R}_{i3}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau+\frac{1}{\omega_i}\int_{\frac{L_3}{v}}^{\frac{L}{v}}\mathrm{R}_{i4}(\tau)\sin\left[\omega_i(t-\tau)\right]d\tau\end{aligned} \qquad (23)$$

Duhamel integral method has been applied to get the solution of Eqn. (19) and Eqn. (23). In MATLAB program, a code has been prepared for this purpose. Different numerical damage scenarios have been exemplified using MATLAB code.

EXPERIMENTAL STUDY

The dynamic investigation of damaged structures under transit loading has been carried out by many researchers theoretically and using various finite elements software. These studies do not reflect a real modeling; instead they provide an approximation to the real models. In order to overcome this limitation, an experimental set-up has been established and the laboratory tests have been executed to validate the results of the numerical and finite elements analysis. The cracks in the beam have been generated using CNC machine. The damaged part of the beam is illustrated in Fig. 2. The structural steel has been chosen as the material. The experiments have been carried out with 1.5 kg and 3 kg transit masses with 451 cm/s and 553 cm/s velocities. The experimental set-up is shown in Fig. 3. During the movement of the transit mass from one end to the other on the damaged beam, the vertical deflections on the beam at the position of moving mass and at the midpoint of the beam have been determined. The motion is provided by A/C motor. The speed of the transit mass can be adjusted by the knob of the A/C motor driver. The connection between the mass and the pulley of the motor has been made with a rope. The distance between the mass and the motor has been set far enough so that the tightness of the rope has been ensured and no slackness is available. The mass is moved on the beam with sliding and the velocity of the mass is supposed to be constant. During the experiments, A/C motor is fixed on the base and the movement is not allowed. During the movement of the transit mass on the beam, the vertical deflection data is obtained by the laser displacement sensors positioned under the beam. Then, these data are transferred to input/output modules where the analog signals are converted to digital signals and the digital signals are transmitted to PLC controller. The data can be accessed on the screen using RSLogix 5000 industrial automation software which is given in Fig. 4. The deflection versus time data can be obtained as .xls file in the program.

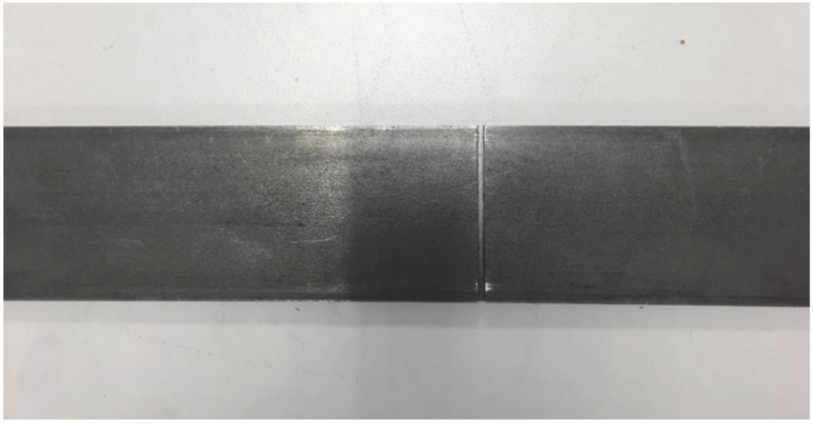

Figure 2: Cracked part of the beam.

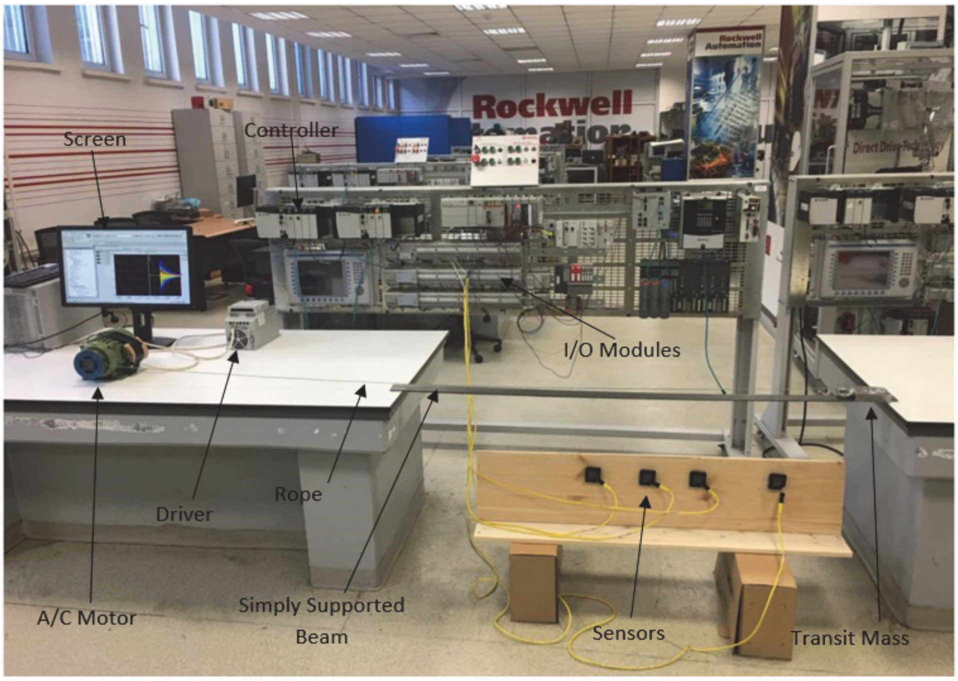

Figure 3: Experimental set-up for damaged simply supported beam.

Tab. 1 demonstrates the elements as well as the specifications of the experimental set-up. The laboratory tests have been repeated around three times to get the desired data. The four set of sample experimental data are considered here. The structural steel beam with dimensions of length L=1.5 m, width W=5cm and the thickness H=0.5cm is considered for the experiment. The results obtained from the experimentation are illustrated in Tab. 3 and 4. The average readings gathered from the experiments have been presented in Tab. 3 and Tab. 4.

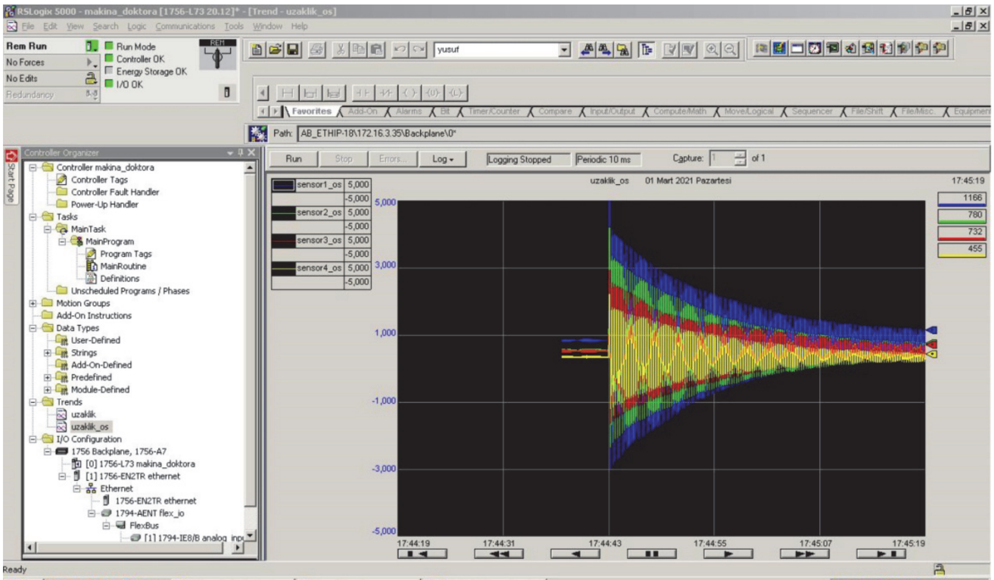

Figure 4: RSLogix 5000 industrial automation software

No	Item	Specification
1	Simply supported beam	L=150cm, W=5cm, H=0.5cm ; $\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.5, 0.7333
2	Beam material	Structural steel (d=7850 kg/m^3, $E = 2x10^{11}\ Pa$)
3	Transit mass	1.5kg and 3kg
4	Sensors	Allen Bradley laser displacement sensors 80-300 mm
5	I/O modules	Flex I/O 1794-IRT8
6	Controller	Allen Bradley Controllogix 5573 PLC controller
7	A/C Motor	A/C 220V 50 Hz/2830 rpm
8	A/C Motor driver	PowerFlex 4M A/C driver
9	Software	RSLogix 5000 industrial automation software

Table 1: The specifications of the elements of the experimental set-up.

NUMERICAL ANALYSIS

This section is devoted to numerical analysis of cracked structures under transit mass to verify the theoretical model with regards to moving mass damaged beam structure. In MATLAB environment, a code has been written for the numerical procedure to determine the dynamic deflection of the damaged simply supported structures under the effect of a moving mass. The results have been illustrated with some graphs including vertical displacements-time data. The numerous damage scenarios of various crack severity, crack positions as well as mass and speed of the transit load have been analyzed.

μ and ζ are the terms used to define the where the crack is positioned in the structure and how severe it is in terms of crack height. Here, ζ and μ are defined as follows:

$\zeta_{1,2,3} = h_{1,2,3} / H$ = relative depth of the first, second and third crack.

$\mu_{1,2,3} = L_{1,2,3} / L$ = relative position of first, second and third crack measured from the left hand side.

In this study, the material of the cracked simply supported beam is selected as structural steel with the dimensions of length L=1.5 m, width W=5cm and the thickness H=0.5cm. M=1.5 and 3kg are the mass magnitudes of transit loads along with the moving speeds v=451 cm/s and 553 cm/s considered in the numerical, FEM and experimental analysis. In the model, the transit mass is moved from one side to the other on the damaged structure with a constant velocity.

FINITE ELEMENTS ANALYSIS

The double cracked beam moving load simply supported structure has been modeled in ANSYS Workbench 2020. The beam dimensions and the crack configuration are the same of those used in experimental and numerical studies. Finite elements analysis has been executed in two parts. First, modal analysis of double cracked simply supported beam has been carried out in ANSYS. First three mode shapes and frequencies ratios of damaged structures have been obtained. The frequency ratio is defined as the frequency of damaged beam over frequency of undamaged beam. Frequency ratios for the first, second and third mode have been calculated 0.9950, 0.9968, and 0.9976 respectively. It has been observed that the cracks in the structure induce a decrease in frequency. Figs.5-7 show the first three shapes of modes and total deformations of cracked beam with $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333 damage scenario with simply supported end states.

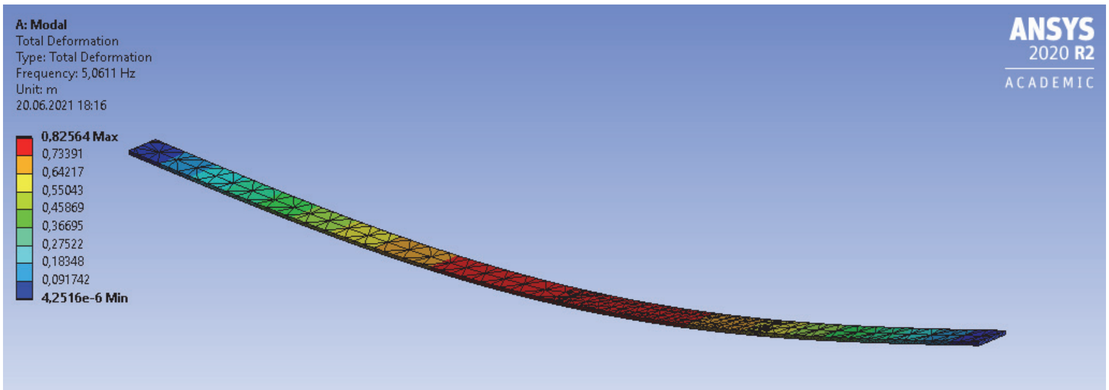

Figure 5: Mode shape # 1 for damaged simply supported structure

In second part of FEA, the transient dynamic analysis has been performed using transient structural module in ANSYS Workbench 2020. In ANSYS, the transient dynamic analysis can be performed utilizing three different methods. These methods are reduced, full and mode superposition methods. Although it is a CPU intensive method, the full method has been selected as the analysis method due to the nonlinearities caused by the centrifugal and Coriolis accelerations terms in the formulation. The damping is neglected in the analysis. Newmark time integration along with constant average acceleration method due to its stability without any condition is taken into account for the FEA. The steps of full method have been embodied to obtain the vertical deflection of damaged structure under a transit mass. The moving mass and cracked beam have been generated in Solidworks and then imported into ANSYS. Fig. 8 illustrates the meshed view of transit mass-double cracked simply supported structure. From Fig. 9, the zoomed view of cracked portion of the structure can be seen. Automatic meshing has been selected in the model, due to meshing capability; tetrahedrons method meshing has been performed. Tetrahedron elements have been assigned in the finite element model of the cracked structure as shown in the zoomed view of the crack (Fig. 9). As the contact algorithm, 'no separation' has been embodied in the model. By applying this function, the transit mass is ensured to move on the damaged beam without any separation.

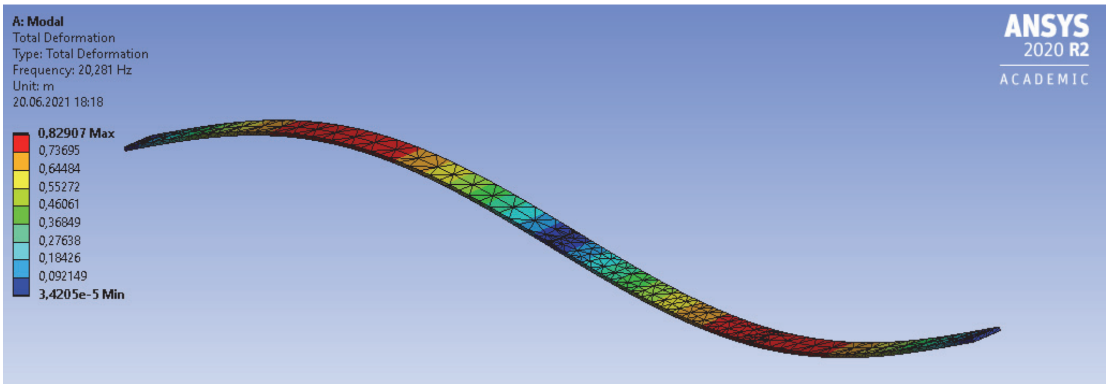

Figure 6: Mode shape # 2 for damaged simply supported structure.

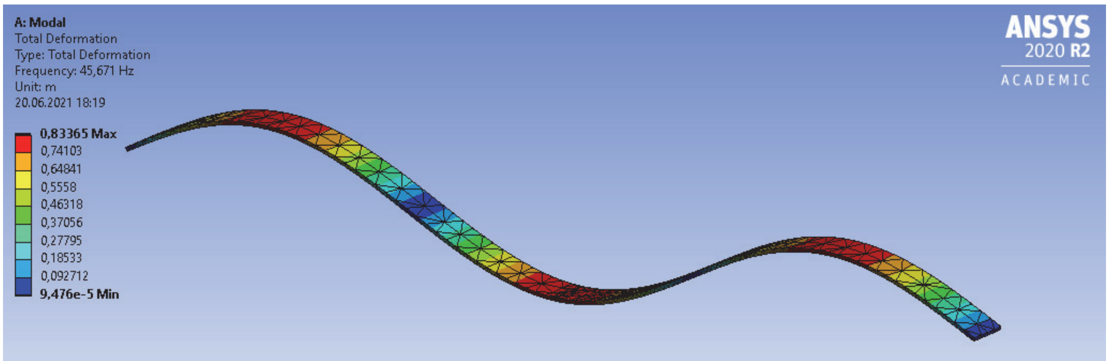

Figure 7: Mode shape # 3 for damaged simply supported structure.

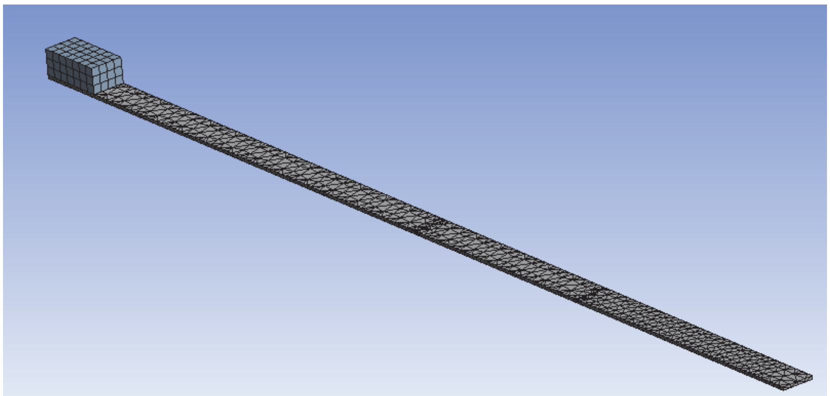

Figure 8: Schematic view of meshing for double damaged structure – transit mass

Fig. 10 demonstrates the transient dynamic analysis of the double cracked beam transit load structure. During the passage of the transit load from one end to the other end on the damaged beam, the vertical deflections of the beam at the location of the transit mass as well as at the mid span of the structure have been obtained.

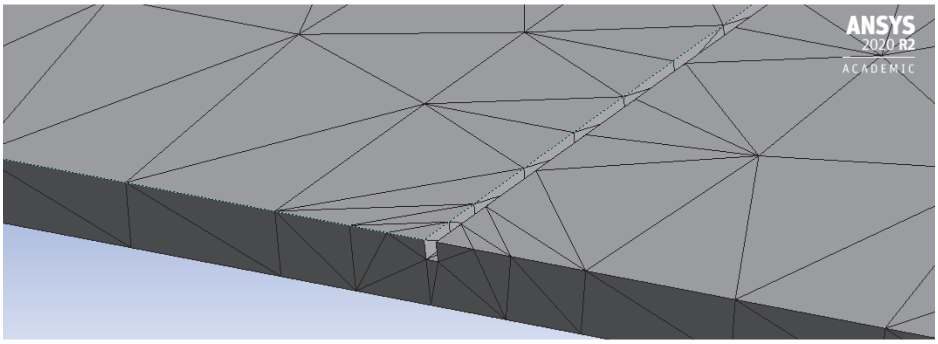

Figure 9: Zoomed view of the crack.

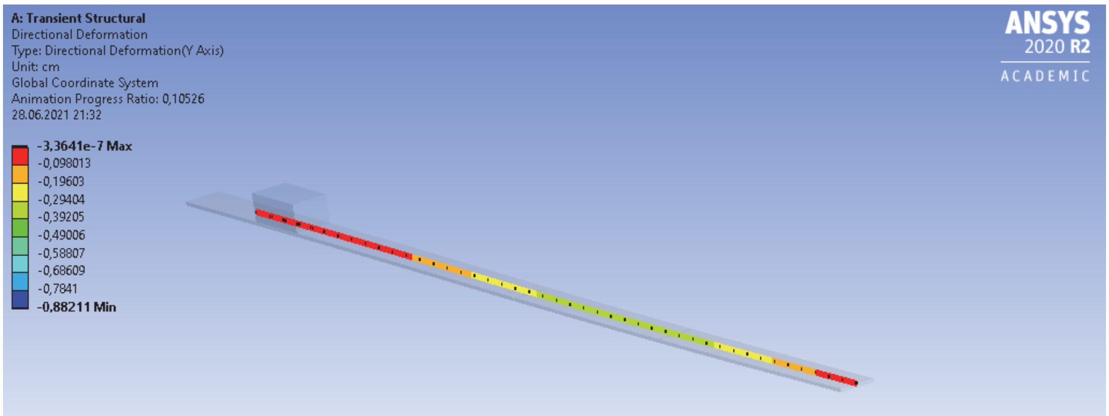

Figure 10: FEA for v= 451 cm/s, M=1.5 kg, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333.

RESULTS AND DISCUSSION

In the scope of this article, double damaged simply supported beam under the effect of a transit load has been handled. Theoretical-numerical model has been established. Using the similar methodology, the formulation for triple cracked beam has been generated. A MATLAB code has been prepared and the equations of motion have been resolved by Duhamel integral method. The numerical analysis has been carried out for different cases to validate the theoretical model and time deflection data have been compared within the graphs. Mode shapes and frequencies of damaged simply supported structure have been determined in ANSYS modal. Using ANSYS Workbench 2020, transient structural analysis of cracked beam under transit load has been performed.

Experiment No	Moving mass	Moving speed	Relative depth of crack	Relative position of crack
1	1.5kg and 3kg	553 cm/s	$\zeta_{1,2}$ = 0.4, 0.5	$\mu_{1,2}$ =0.5, 0.7333
2	1.5kg and 3kg	451 cm/s	$\zeta_{1,2}$ = = 0.4, 0.5	$\mu_{1,2}$ =0.5, 0.7333

Table 2: Data set for experiment.

Finally, numerical and FEA model have been verified by experimental tests in the laboratory. Fig. 11 shows how close the results of numerical, FEA and experimental results are and the study has been validated.

Within Tab. 3, the comparison of the experimental and numerical results for v= 553 cm/s, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333 double damaged simply supported structure is given while comparison of FEA and the experimental results for v= 451 cm/s, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333 double cracked simply supported beam is presented in Tab. 4.

The errors between numerical and experimental have been to be 3.85% while, those between FEA and experimental to be 2.51 respectively. It has been proven that the theoretical and FEM models approximate to real model with the acceptable deviations.

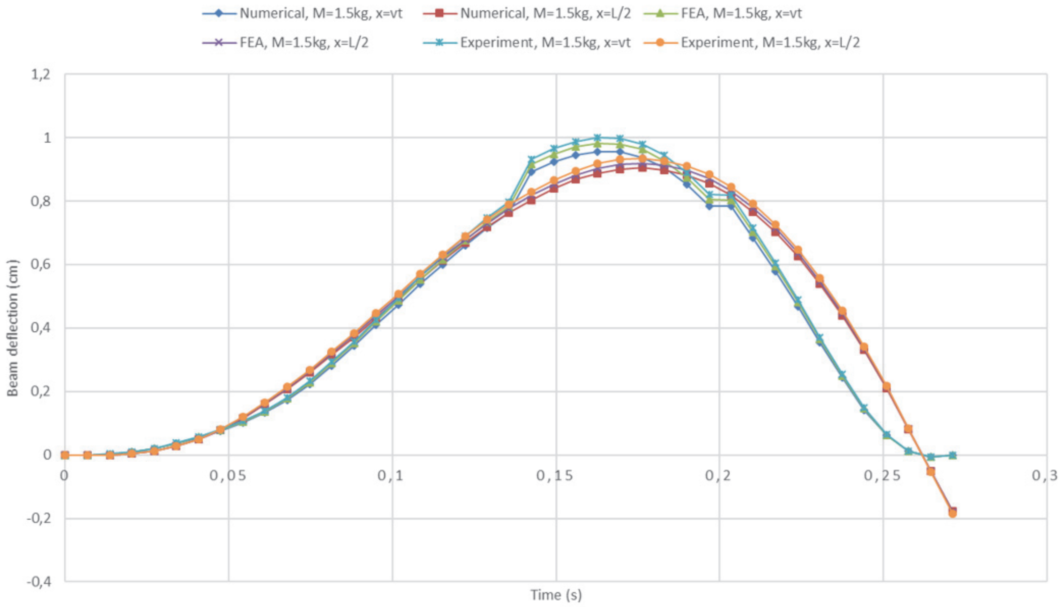

Figure 11: Time(s) – deflection (cm) data for numerical, FEA and experimental studies for v= 553 cm/s, M=1.5 kg, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333

	Numerical				Experimental			
	x=vt		x=L		x=vt		x=L	
time (s)	M=1.5 kg	M=3kg	M=1.5kg	M=3kg	M=1.5kg	M=3kg	M=1.5kg	M=3kg
0.0203	0.0092	0.0172	0.0035	0.0067	0.0097	0.0178	0.0039	0.0071
0.0746	0.2233	0.4021	0.2597	0.4735	0.257	0.435	0.267	0.475
0.0882	0.3434	0.6113	0.3719	0.6678	0.382	0.652	0.396	0.702
0.1153	0.6009	1.0863	0.6118	1.1004	0.613	1.127	0.633	1.137
0.1221	0.6604	1.201	0.6671	1.2109	0.672	1.235	0.682	1.275
0.1424	0.8929	1.6846	0.8035	1.5144	0.929	1.72	0.82	1.59
0.1899	0.853	1.9323	0.8828	1.9748	0.869	1.966	0.895	1.996
0.2034	0.7836	1.9478	0.8174	1.9885	0.791	2.104	0.83	2.224
0.2238	0.4692	1.3928	0.627	1.8526	0.477	1.442	0.643	1.8579
0.2577	0.0118	0.1391	0.0816	0.8995	0.0123	0.1399	0.0825	0.919
Average % deviation					4.44	3.87	3.31	3.78
Total % deviation					3.85			

Table 3: Time (s) - deflections (cm) data for numerical and experimental studies for v= 553 cm/s, $\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.5, 0.7333

The percentages of errors between the numerical and experimental studies as well as the FEA and the experimental studies have been determined for two masses and speeds as per the following equation:
The deviation of numerical values from experimental data can be stated as
(Experimental-Numerical) x 100/Experimental
The deviation of FEA results from experimental values can be expressed as
(Experimental-FEA) x 100/Experimental
Average % deviation is considered as the sum of % deviations divided by total number of selected deflections whilst total % deviation is defined as the sum of the average % deviations over total number of average % deviations. It has been seen from the analysis that % deviations in total are 3.85 and 2.51 for numerical and FEA investigations respectively. It has been understood that the numerical and FEA results are very close to experimental values. Thus, the method in ANSYS, Newmark's time integration method and the Duhamel integral technique for the numerical analysis have been confirmed that they can be used to get the deflections of the damaged beams subjected to moving load.

	FEA				Experimental			
	x=*vt*		x=L		x=*vt*		x=L	
time (s)	M=1.5 kg	M=3kg	M=1.5kg	M=3kg	M=1.5kg	M=3kg	M=1.5kg	M=3kg
0.0166	0.0037	0.00689	0.00065	0.0013	0.0097	0.0178	0.0039	0.0071
0.0831	0.24186	0.4183	0.29973	0.51841	0.257	0.435	0.267	0.475
0.0915	0.29973	0.5498	0.35596	0.619	0.382	0.652	0.396	0.702
0.1164	0.51104	0.9121	0.55125	0.98194	0.613	1.127	0.633	1.137
0.1414	0.68448	1.2812	0.70862	1.3136	0.672	1.235	0.682	1.275
0.1663	0.78074	1.5603	0.78174	1.5603	0.929	1.72	0.82	1.59
0.2245	0.68921	1.7187	0.68167	1.7048	0.869	1.966	0.895	1.996
0.2328	0.61358	1.6152	0.64105	1.6505	0.791	2.104	0.83	2.224
0.2661	0.332	1.0463	0.38183	1.2245	0.477	1.442	0.643	1.8579
0.2993	0.0569	0.22331	0.0922	0.4678	0.0123	0.1399	0.0825	0.919
Average % deviation					3.74	1.33	2.39	2.54
Total % deviation					2.51			

Table 4: Time(s) - deflections (cm) data for FEA and experimental studies for v= 451 cm/s, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333

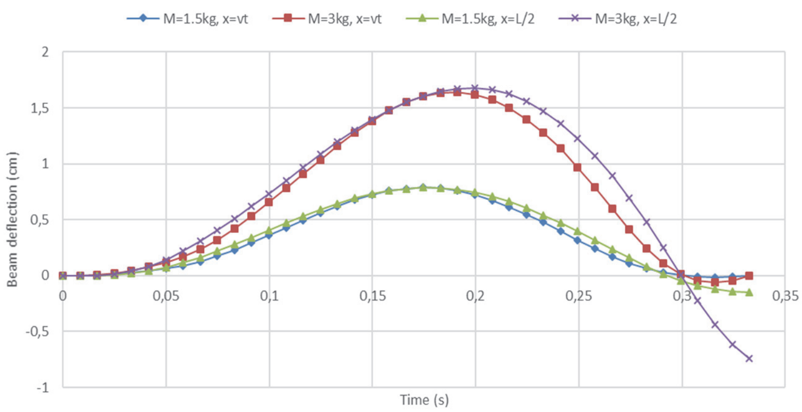

Figure 12: Time-deflection for v= 451 cm/s, undamaged structure.

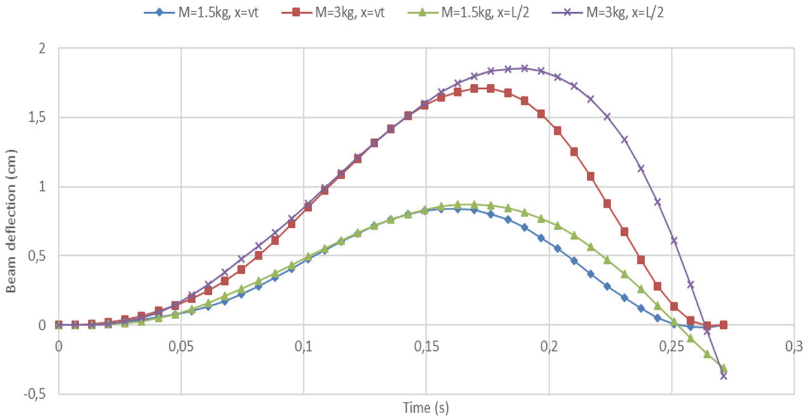

Figure 13: Time-deflection for v= 553 cm/s, undamaged structure.

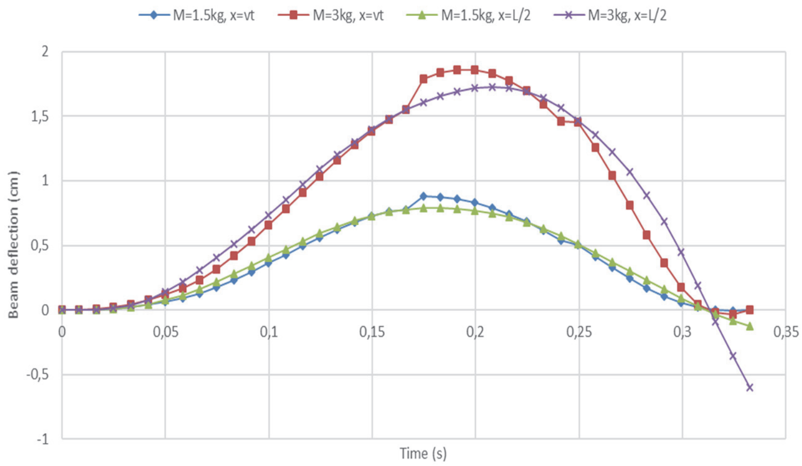

Figure 14: Time-deflection for v= 451 cm/s ,$\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.5, 0.7333.

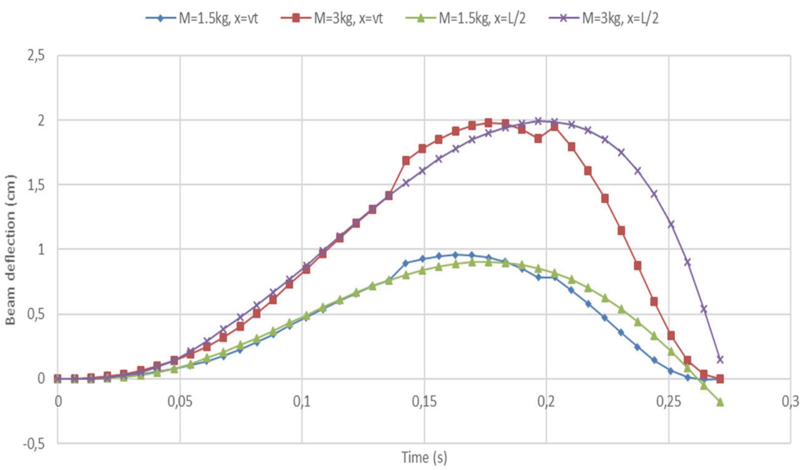

Figure 15: Time-deflection for v= 553 cm/s ,$\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.5, 0.7333.

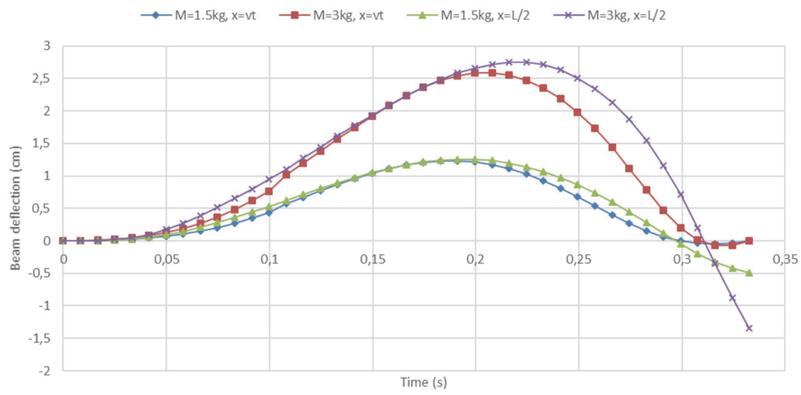

Figure 16: Time-deflection for v= 451 cm/s, $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.1333, 0.3.

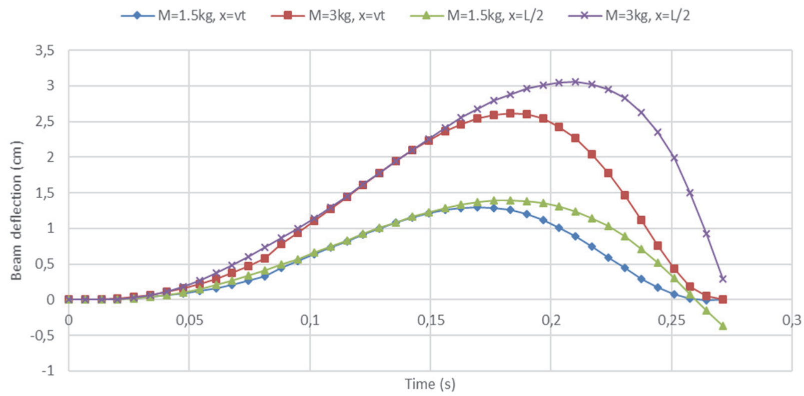

Figure 17: Time-deflection for v= 553 cm/s ,$\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.1333, 0.3

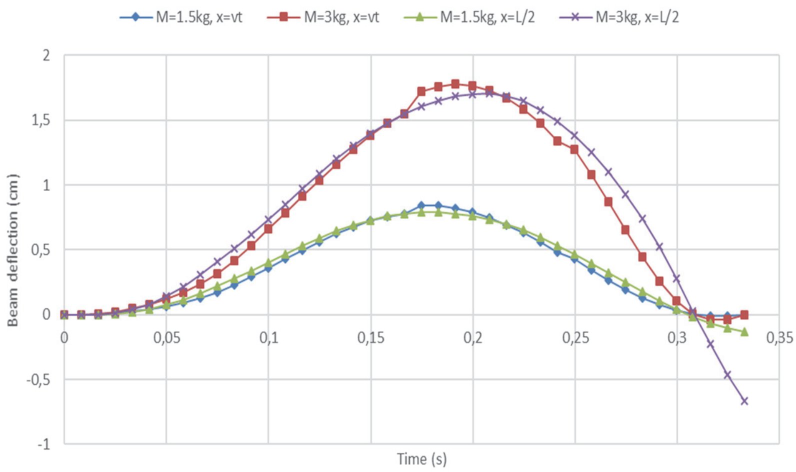

Figure 18: Time-deflection for v= 451 cm/s ,$\zeta_{1,2}$ = 0.25, 0.35 , $\mu_{1,2}$ = 0.5, 0.7333.

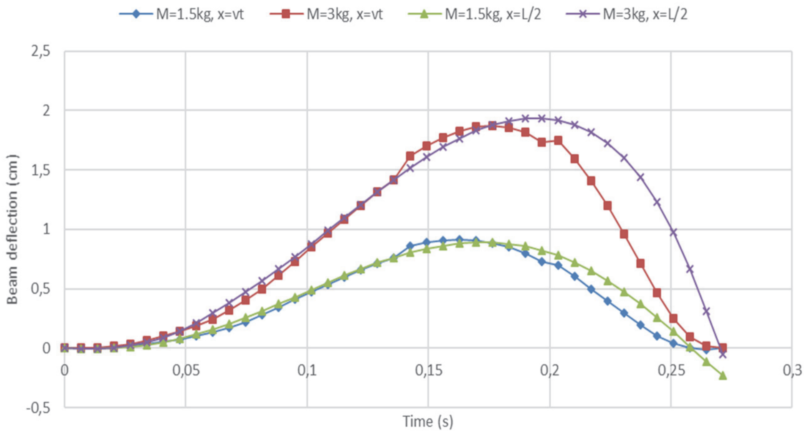

Figure 19: Time-deflection for v= 553 cm/s , $\zeta_{1,2}$ = 0.25, 0.35 , $\mu_{1,2}$ = 0.5, 0.7333.

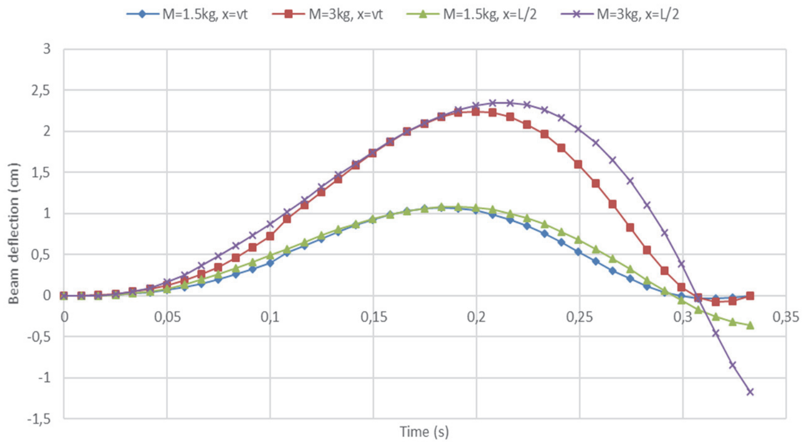

Figure 20: Time-deflection for v= 451 cm/s , $\zeta_{1,2}$ = 0.25, 0.35 , $\mu_{1,2}$ = 0.1333, 0.3.

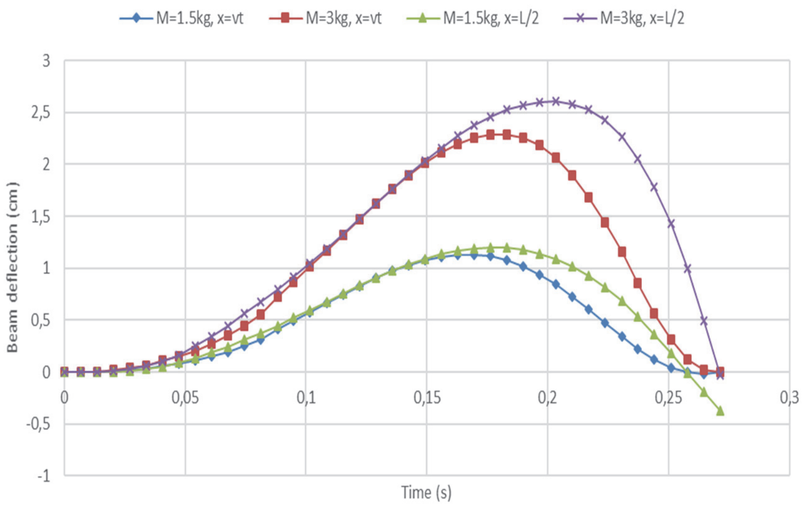

Figure 21: Time-deflection for v= 553 cm/s , $\zeta_{1,2}$ = 0.25, 0.35 , $\mu_{1,2}$ = 0.1333, 0.3.

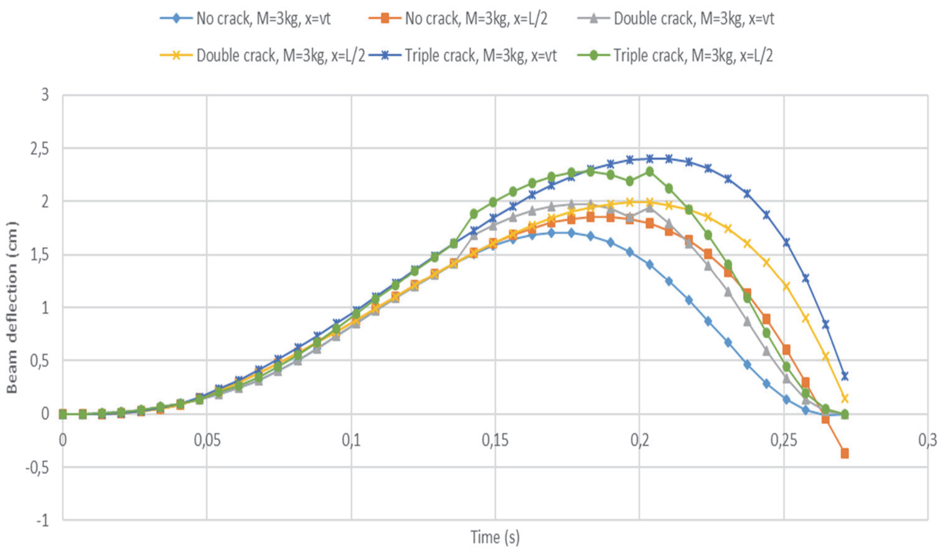

Figure 22: Time(s) – deflection (cm) data for numerical studies for v= 553 cm/s, M=3 kg for undamaged, double cracked $\zeta_{1,2}$ = 0.4, 0.5 , $\mu_{1,2}$ = 0.5, 0.7333 and triple cracked $\zeta_{1,2,3}$ = 0.3, 0.4, 0.5 , $\mu_{1,2}$ = 0.2, 0.5, 0.7333.

In the meantime, the deflections at $x=vt$ which refers to the location of the load at any time t during the movement and at $x=L/2$midpoint of the structure have been obtained. The results have been shown within the plots shown in Fig. 12-21 with a comparative approach. With the enhancement of the crack depth the vertical displacement of the beam also amplifying. If the crack positions are far away from the starting end of the transit mass, the vertical displacements of the beam are decreasing.

From the analysis and observation of Figs 14-19, there is showing discontinuities in the nature of the curve. The discontinuities or sudden increase in the beam deflections are appearing only due to the presence of cracks and it is particularly happening at the crack locations.

In Fig. 22, comparison of numerical data for v= 553 cm/s, M=3 kg for undamaged, double cracked $\zeta_{1,2}$ = 0.4, 0.5, $\mu_{1,2}$ = 0.5, 0.7333 and triple cracked $\zeta_{1,2,3}$ = 0.3, 0.4, 0.5, $\mu_{1,2}$ = 0.2, 0.5, 0.7333 beams are given. From this graph, it is clearly understood that the increase of amount of cracks in the beam causes the enhancement of vertical displacements of the beam. This result has also been validated by the works in literature by Esen [32] and Lal [33].

Conclusion

In this present work, the influences of crack numbers, crack depth, crack location as well as the mass and speed of the moving load on the vibration behavior of damaged beam under transit loading with simply supported end states have been researched. The analysis has been carried out computationally with both MATLAB and ANSYS and it has been validated experimentally. The followings can be mentioned as the conclusions gathered from this analysis. Relatively higher speed induce a slight increase of deflection. With regards to the effect of transit mass, it can be stated that heavier the load is, higher the deflection is. When the amount of the cracks in the beam is increased, the deflections also increase. Enhancement of the crack depth causes the deflections go up. If the crack gets far from the left end which is the point where the motion begins, the vertical deflection of beam decreases. The beam behaves more rigid in undamaged case and the cracks in the beam cause an increase in local flexibility which is detrimental for the structure. The number, depth and position of the crack, the mass and the velocity of the transit load influence the dynamic response of the damaged structure. The deflections of the cracked structures are mostly affected by the mass magnitude of the moving load compared to the crack features. For the future studies, the effects of braking and acceleration of the transit mass can be explored under various foundations.

ACKNOWLEDGEMENTS

The authors are grateful to the laboratory staff in Power, Motion and Process Control (Rockwell Automation) Laboratory in Istanbul Technical University for the permission of laboratory access and the preparation of the experimental set-up along with the programming of PLC controller.

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